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Evaluation of a pyrometric-based temperature measuring process for the laser transmission welding

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Abstract

An on-axis pyrometric-based temperature measurement method suitable for different laser transmission welding techniques is presented. A temperature detection during contour and quasi-simultaneous welding is demonstrated to fit the requirements of laser transmission welding with part adapted temperature fields. For the experiments a pyrometer is connected to a scanner optic with a non-color-corrected lens. The experiments are performed with a high-speed pyrometer detecting in spectral range of 1.65 - 2.1 µm. Potential errors caused by the measurement method are evaluated and its limits depend on the welding technique performed are examined by creating different defects in the weld seam.

Keywords: Laser transmission welding; pyrometer; contour welding; quasi-simultaneous welding

1. Introduction and motivation

Laser transmission welding of thermoplastic materials is an established industrial technology used for joining parts due to its high flexibility and short cycle times [1]. During laser transmission welding of overlap connections laser radiation transmits through the upper thermoplastic part and is absorbed by a lower material. Heat is developed in the laser absorbing part, which melts the thermoplastic locally. Due to heat conduction, the laser transparent part melts locally too. Thermoplastic materials are laser radiation

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absorbing, when the material contains e.g. carbon black, absorbing additives, pigments or when the materials are reinforced with carbon fibers [2, 3]. Furthermore, the absorption coefficient can be adjusted by the filler concentration of carbon black or other absorbing additives [3].

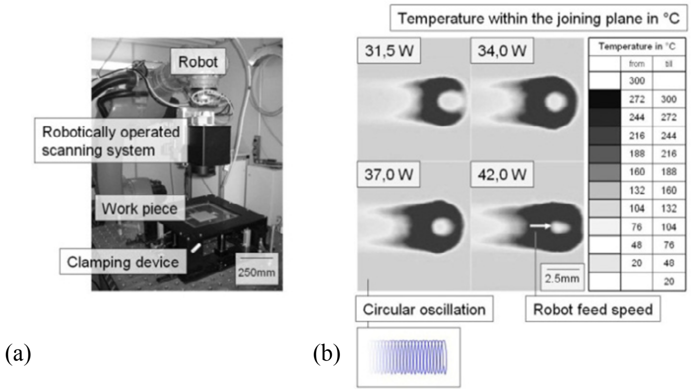

Fig. 1. (a) Photograph of the system technology suitable for laser transmission welding with part adapted temperature fields; (b) infrared camera images monitored while welding with circular oscillation of the laser beam affected by the scanning system

The laser transmission welding technique can be divided into contour, quasi-simultaneous, simultaneous and mask welding. During contour welding, the laser beam passes the weld seam contour only once. During quasi-simultaneous welding, the laser beam is guided by a scanner optic over the welding area more than once [4, 5]. The quasi-simultaneous welding technique is known for its advantage of good gap bridging capability [6]. Today, the interest in joining larger thermoplastic parts with three-dimensional formed weld seams by laser transmission welding is rising. In order to obtain these requirements, the welding technique used is contour welding. The parts have to be clamped nearly gap-free, because gaps in between the joining partners may result in processing issues, such as welding failures, poor achievable process speed or low weld seam strengths in the case of contour welding. The gap bridging capability of contour welding has been determined to be on the order of ten micrometers, which is relatively small when compared to gap bridge capability of quasi-simultaneous welding. For better gap bridging capability, laser transmission welding of part adapted temperature fields was introduced [7]. The aim of this new welding technique, suitable for three dimensional formed weld seam contours, is to elongate the melt pool without thermally damaging the joining partners through the use of tailored intensity distributions. As shown by Fig. 1a, a robotically operated scanning system is used. Using a scanning system, different intensity distributions can be formed. Also, it is possible to change the intensity distribution depending on the process needs, by changing the figure drafted by the scanning system quickly. In addition, the robot can be used to guide the scanning system along any three dimensionally formed weld seam. Also, shown by Fig. 1b are several thermo camera images, which were obtained with a mercury cadmium telluride camera mounted off-axis. The angle between the incident laser beam and the infrared camera optical axis was set to be $\alpha = 45$ ° and the camera was moved together with the scanning system. In the experimental investigation, the maximum melt pool length was dws = 12.7 mm formed with a laser power of P = 42 W. A circular scanning figure was used to oscillate the laser beam emitted by a fiber guided diode laser. The melt pool formed by the circular oscillation is significantly longer than a melt formed by conventional contour welding and without thermally damaging the polymer, e. g. within the centre of the weld seam (Fig. 2). The heat affected zones normal to the robot feed speed for no oscillation and a circular oscillation are depicted in Fig. 2. The weld seam in Fig. 2a was generated using contour welding without oscillation. The weld seam represented by Fig. 2b was manufactured using laser transmission welding with part adapted temperature fields by a circular oscillation of the laser beam. The circular figure drafted by the scanning system had a diameter of dfig = 1.5 mm and was welded with a velocity of v = 2.500 mm · s-1. The weld seam produced without oscillation is dws = 550.0 µm wide, hws = 318.0 µm high and has a lenticular shape, which is common for weld seams manufactured using contour welding. In contrast, the circular oscillation of the laser leads to a druzy shaped heat affected zone, and a significantly wider weld seam. The manufactured weld seam has a width of dws = 1,509.6 µm and a height of hws = 258.0 µm. When the melt pool becomes broader (cp. Fig. 2b) and longer (cp. Fig. 1b), a larger molten volume expands and the extra melt bridges larger gap sizes between the joining partners. In addition, due to the longer melt pool for the same feed velocity, more time remains for heating and local melting of the upper joining partner and for the interactions of the melt, which is increasing the load-bearing strength of the joint. Also, temperature gradients are decreasing for the heating as well as the cooling phase compared to contour welding. Fig. 1 further depicts for this case that the temperature field is depending on different process parameters like the laser power. Therefore a pyrometric-based temperature measuring method for a online process control of the new laser transmission welding process is necessary e.g. to control the laser power or parameters defining the beam oscillation and to switch the diameter of the oscillation figure or the figure itself in order to obtain the desired part adapted temperature fields and to fulfill process needs.

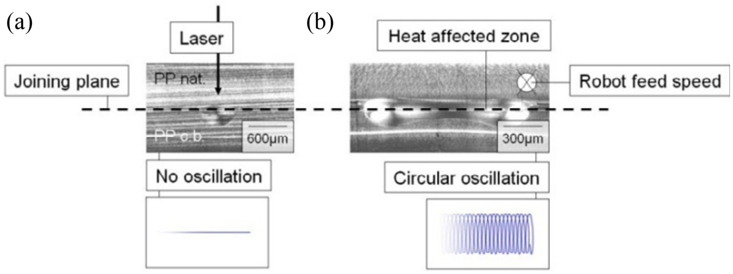

Fig. 2. Weld seam cross sections manufactured by conventional contour welding without beam oscillation (a) as well as contour welding with part adapted temperature fields using circular beam oscillation (b)

Former work has shown that the heat development in a weld seam between a short glass fibre reinforced thermoplastic and a carbon fibre reinforced thermoplastic composite can be controlled with a pyrometric-based method. The welding technique performed was contour welding [8]. A pyrometric-based temperature detection includes measurement deviations for example due to objects in the sight field of the pyrometer as well as when the target is moved [9]. Furthermore, when the pyrometer spot is guided parallel to the laser radiation through a scanner optic with a standard f-theta lens, a position shift occurs between the two spots, because the lenses of the optic are not achromatic. To decrease this shift, the movement of the laser and pyrometer spot has to occur close to the centre of the optic [10].

In this article, the temperature measurement method was adapted, which is used for the contour welding process, for the quasi-simultaneous welding technique. Therefore, an on-axis temperature detection technique is developed by connecting a pyrometer to a non-colour corrected scanner optic. The error of measurement of this method and the limits of this procedure are evaluated. This temperature detection technique can be used to control the temperature propagation in part adapted temperature fields during the welding of complex parts.

2. Experimental set-up

The welding experiments are performed with a diode laser produced by Laserline GmbH. This laser emits at a wavelength of λ_L = 940 nm and provides a maximum output power of P_{max} = 300 W. The laser radiation is guided to the scanner optic by an optical fibre. The laser beam diameter is d_f = 2.5 mm in the focal point. The temperature measurement is executed by a high-speed pyrometer produced by Sensortherm GmbH, which is connected to the scanner optic (Fig. 3a). The pyrometer detects temperatures between T = 120 - 520 °C in a spectral range of λ_P = 1.65 - 2.1 µm. This spectral range allows detection through the upper thermoplastic part, which is partly transparent in this measurement range. The experiments are carried out with a sample rate of f = 13.5 kHz.

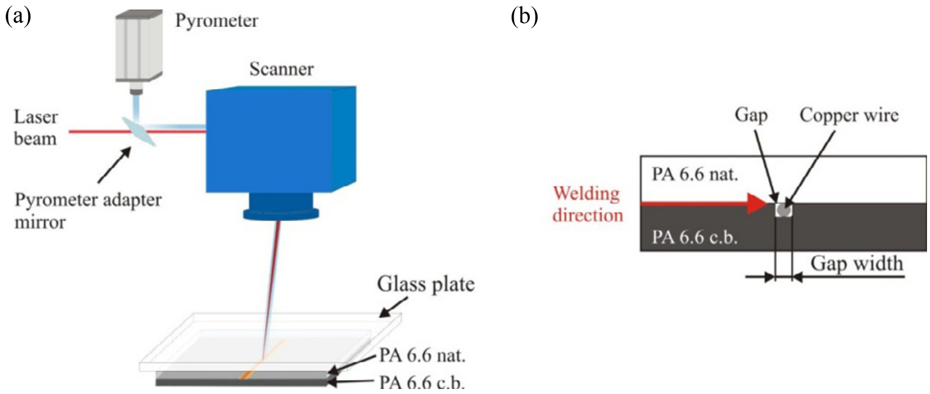

Fig. 3. (a) schematic of the Experimental set-up for the temperature detection during laser transmission welding; (b) schematic of the test sample with gap and copper wire in the laser absorbing material

The materials used are a laser transparent polyamide natural (PA 6.6 nat.) and a laser absorbing polyamide with the additive carbon black (PA 6.6 c.b.). To mimic defects in the d_w = 26 mm long weld seam, gaps of three different widths were ablated into the absorbing material by ultra violet laser radiation. The widths of the gaps are w_1 = 0.75 mm, w_2 = 0.42mm and w_3 = 0.36 mm (Fig. 3b). The pieces are clamped between a base plate made of Teflon and a glass substrate with a clamping pressure of $p = 2.0 \cdot 10^5$ Pa.

3. Results and Discussion

The shielding of the pyrometer signal and a position shift of the laser and pyrometer spot to each other due to the non-color-corrected lens is investigated. Additionally, the system performance of an on-axis temperature measurement by a pyrometer is investigated. Defects, specifically laser generated gaps, are created in the welding area, which contain in some cases a copper wire. The copper wire mimics contaminant in the thermoplastic material and has a higher heat conductivity than the PA6.6. In the experiments, the welding velocity is varied in steps of v = 100 mm/s to determine the maximum welding velocity, which still allows a detection of defects depending on the defect size.

3.1. System performance of pyrometer based temperature measurement

The detected temperature value of the pyrometer is affected by the shielding of the scanner optic, the laser transparent part and the glass plate. Therefore, different temperatures are generated with a heating panel and a PA 6.6 nat. part with a glass plate placed d_h = 5 mm above the heating panel. The temperature on the boundary between the heating panel and the thermoplastic is determined to observe the temperature loss through the objects in the sight of the pyrometer. A comparison between the differences of the true temperature displayed on the heating panel and the temperature measured by the pyrometer indicates that the inaccuracy increases from $T_{\Delta,min}$ = 109 °C to $T_{\Delta,max}$ = 125 °C as the true temperature varies between T = 240 - 277 °C. It is determined that the detected temperature is not the real temperature. For that reason, the measured temperature by the pyrometer will be referred to as relative temperature (T_{rel}).

The position of the pyrometer spot with respect to the laser spot is determined. The laser spot is aligned at the middle of the scan field and a heat source is placed directly at the laser spot (Fig. 4).

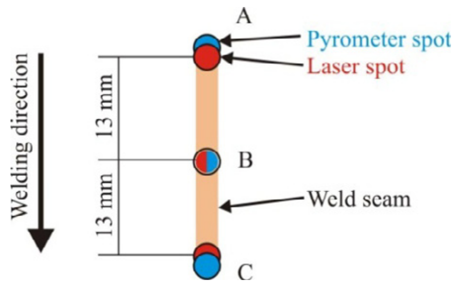

Fig. 4. Schematic description of the relation between laser and pyrometer spot position

The mirror in the pyrometer adapter is adjusted to place the pyrometer spot to the same position of the laser spot and the point heat source. To evaluate the shift between the laser and the pyrometer spot, the laser spot is moved d = 13 mm from the center (position A, C). The non-centric position of the pyrometer spot is determined with the point heat source. It is observed that the pyrometer spot is located further from the center than the laser spot. This is shown in Fig. 4 at the positions A and C. This position shift is caused by different refractive indices due to the different operating wavelengths of the laser and the pyrometer. The movement of the pyrometer and laser spot during welding can be divided into three positions. In position A, the pyrometer spot is behind the laser spot in the welding direction. In position B both spots are at the same point. The pyrometer spot starts to move ahead of the laser spot (position C). This indicates that the position between the laser and pyrometer spot is changing during the welding process and can cause errors in the temperature measurement.

3.2. Temperature measurement during contour welding

Contour laser welding experiments are performed with test samples with different gap sizes to mimic the temperature change due to defects to evaluate the described temperature measurement method. In Fig. 5a the measured relative temperature as a function of time for a sample with a gap size w1 is depicted. After t = 0.01 s the temperature rises for about t = 0,005s, which indicates a heat build-up caused by the gap of a width w1 = 0.75 mm. Heat accumulation is observed due to the reduced heat conduction between laser absorbing and transmitting thermoplastic at the gap. Furthermore, a copper wire is placed in the gaps (diameter of the copper wire is d1 = 0.51 mm for the gap w1 and d2 = 0.25 mm for the gap w2). In Fig. 5b, the relative temperature during the contour welding is shown. As the laser radiation reaches the gap Trel increases. The heat conductivity of copper is larger than the one of PA 6.6 c.b., therefore, the measured temperature drops when the copper wire is reached. It is defined, that a defect is detected when the relative temperature changes for more than T = 5 °C.

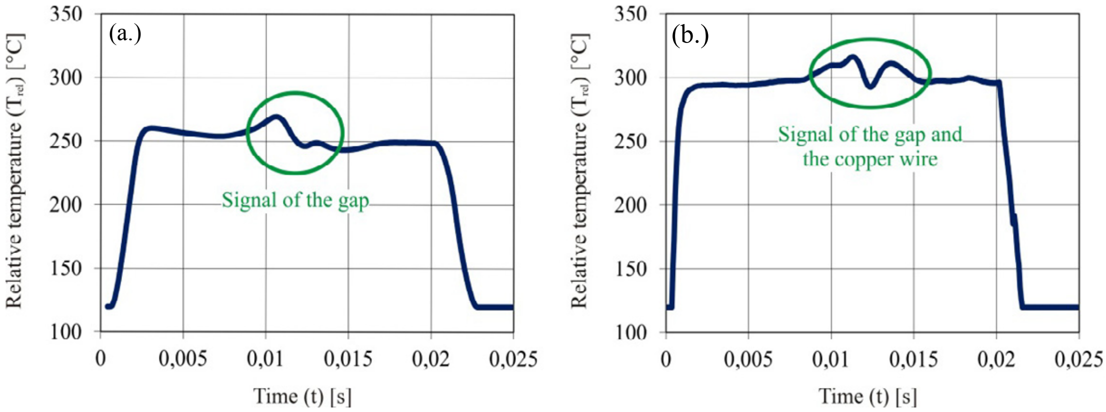

Fig. 5. Relative temperature as a function of time measured by a pyrometer during contour welding with v = 1000 mm/s; (a.: defect consisting of a gap (w_1 = 0.75 mm) detected at a laser power P = 270 W, b.: defect consisting of a gap (w_1 = 0.75mm) and a wire (d_1 = 0.51 mm) detected at a laser power P = 300 W)

3.3. Temperature measurement during quasi-simultaneous welding

During quasi-simultaneous welding, the temperature in the weld seam rises for each repetition the laser radiation passes the weld seam. In Fig. 6, T_{rel} after six welding repetitions is depicted. The defect in the absorbing part consists of a gap (w_3 = 0.75 mm) and a copper wire (d_1 = 0.51 mm). It is observed that the decrease of T_{rel} in the first welding repetition is smaller than in the last repetition. Also, the width of the decrease of T_{rel} increases for each repetition. During welding, the material melts and starts to enclose the wire, which enables heat conduction to the wire and out of the weld seam.

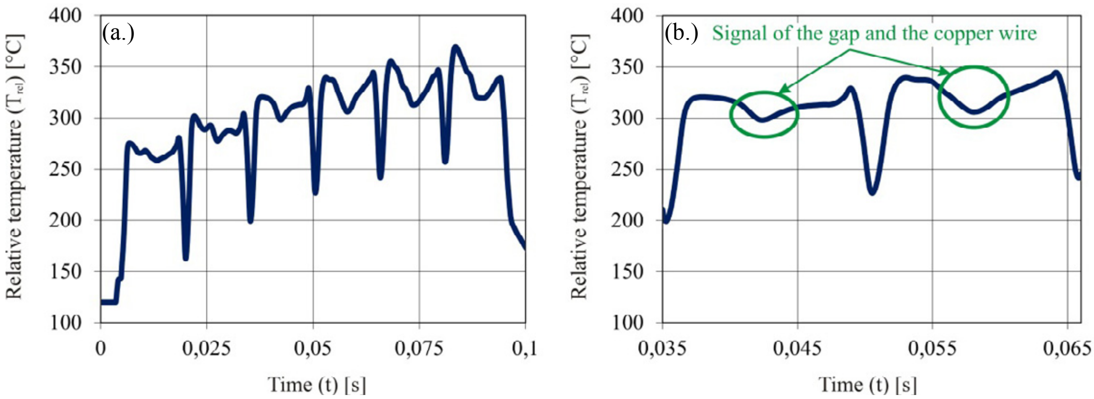

Fig. 6. Relative temperature as a function of time measured by a pyrometer during quasi-simultaneous welding (a.: temperature development over 6 repetitions, b.: optical enlargement of two welding repetitions)

Furthermore, the heat development is measured for the quasi-simultaneous welding with a sample containing only gaps. The heat accumulation in the weld seam rises with every welding repetition. In the area of the gap T_{rel} rises (Fig. 7). Also, during the welding repetitions the signal peak caused by the gap decreases compared to the average weld seam temperature. The material melts and could flow into the gap. This could lead to a decrease of the gap size, and also could cause a decrease of the temperature signal.

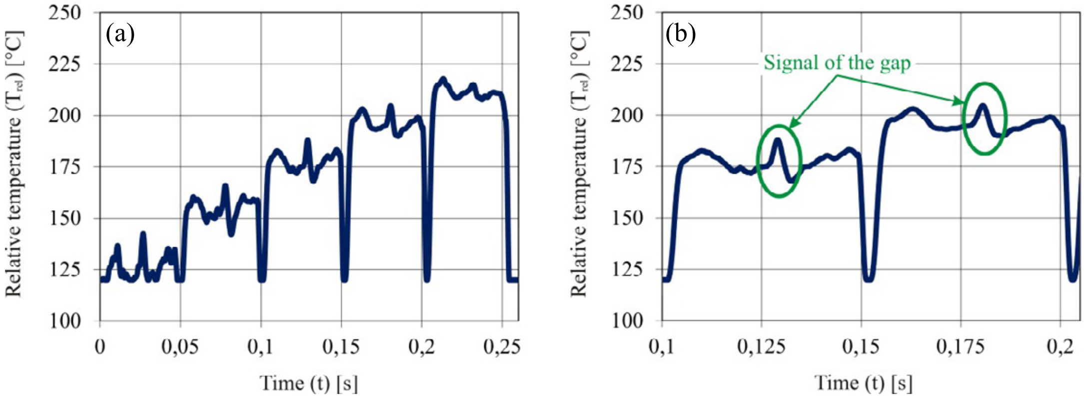

Fig. 7. Relative temperature as a function of time measured by a pyrometer during quasi-simultaneous welding of a sample containing a gap (a: temperature development over 5 repetitions, b: optical enlargement of two welding repetitions)

3.4. Achieved welding velocities depending on defect size

The welding velocity for the contour (C) as well as the quasi-simultaneous welding (QS) technique is increased until a clear identification of the previously described defects is not possible anymore (Fig. 8) and without taking into account the achieved weld seam quality. The gap w_1 containing a wire is detectable at larger velocities than with only a gap of the width w_1.

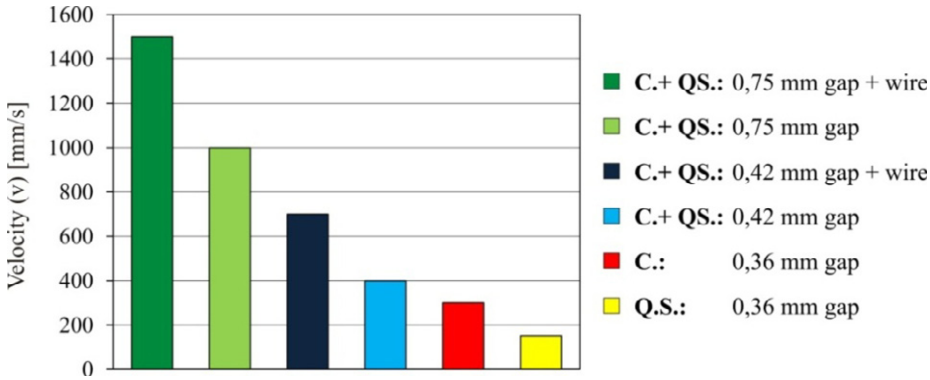

Fig. 8. Maximum welding velocity for detecting different defect sizes for the contour (C) and quasi-simultaneous (QS) welding technique

This indicates that the measuring method and its resolution depend on the type of defect present. To detect small defects for both welding techniques the welding velocity has to be decreased. At a gap size w_3 the maximum welding velocity for contour welding is larger than that for quasi-simultaneous welding technique. During quasi-simultaneous welding the heat development is slower than for contour welding. Additionally, the measured relative temperature is decreased due to shielding of the pyrometer signal as described earlier. Also, molten material could fill a small gap before a clear signal of the gap temperature is detected.

4. Conclusion

After addressing laser transmission welding with part adapted temperature fields, in this paper investigations on an on-axis temperature detection method by an on-axis pyrometer for the laser transmission welding using a non-colour-corrected optic are presented. Possible errors of the measurement method are described, such as the position shift between the laser and pyrometer spot depending on the position in the scanning field. Furthermore, the temperature profiles of two different kinds of defects in the weld seam are evaluated for contour and quasi-simultaneous welding. It is shown that a gap in the laser radiation absorbing material causes a temperature increase while a copper wire in the gap leads to a temperature decrease. For the experimental set-up, the maximum welding velocities were determined, which still enable to detect the regarded defects in the absorbing material. For a gap width of w_1 = 0.75 mm a maximum welding velocity of v = 1000 mm/s was determined. For the same gap width containing a wire a maximum welding velocity of v = 1500 mm/s was reachable. Based on these preliminary results, it is the author's intention to further improve the temperature measurement by investigating the deviation of the pyrometer spot shift and generating a correction program. This procedure can enhance the detection of smaller defects also. Furthermore, the temperature detecting method will be implemented as a quality control strategy for the laser transmission welding of part adapted temperature fields.

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